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Network Performance Evaluation for Nyquist-WDM-Based Flexible Optical Networking

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Abstract *We focus on the spectrally efficient Nyquist-WDM concept and quantify the effect of physical layer design parameters on the network level performance. Case studies are conducted on a realistic reference network under different traffic demand settings and trade-offs with respect to the utilized spectrum and the required transponders are identified.*

Introduction

As bandwidth-hungry applications are continuously emerging, technologies enabling high spectral efficiency become a necessity. Multiple tightly spaced channels can be combined in spectrally efficient tunable “superchannels” offering bit-rates in the terabit per second range. Recently, the Nyquist WDM (N-WDM) concept has emerged as an alternative to optical coherent OFDM (Co-OFDM) as an approach to form such superchannels[1,2]. In N-WDM the subcarriers are spectrally shaped so that they occupy a bandwidth close or equal to the Nyquist limit for inter-symbol-interference-free and cross-talk-free transmission. However, while the performance of Co-OFDM has been evaluated on the network level[3] – very few studies exist on the performance evaluation of N-WDM on the network level[4].

In this paper we focus on the promising N-WDM concept and quantify the effect of physical layer design parameters on the network level. Multiple options are examined with respect to the modulation format, the symbol-rate, the subcarrier spacing, and the launch power. These options have a direct effect on the offered effective bit-rate, the maximum transparent reach, and the required spectrum. Hence, it is critical to tune them targeting the maximum overall efficiency on the network level.

Case studies are conducted on a realistic reference core network under different traffic demand settings and occurring trade-offs are identified. As conventional routing and wavelength assignment (RWA) algorithms are not applicable in flexible networks, we develop an extended version of the routing modulation level and spectrum allocation algorithm (RMLSA) from[3]. In this paper, special attention is given for the first time to the following questions:

1. Assuming that the symbol rate is set to constant value in all superchannels throughout the network - what are the tradeoffs when selecting this value?
2. Can additional benefits be reaped if the symbol rate is allowed to vary in different superchannels?

We quantify tradeoffs in terms of spectrum and transponder savings. It is shown that significant savings can be achieved by allowing the symbol rate to be dynamically tuned, when fixed power spectral density is assumed.

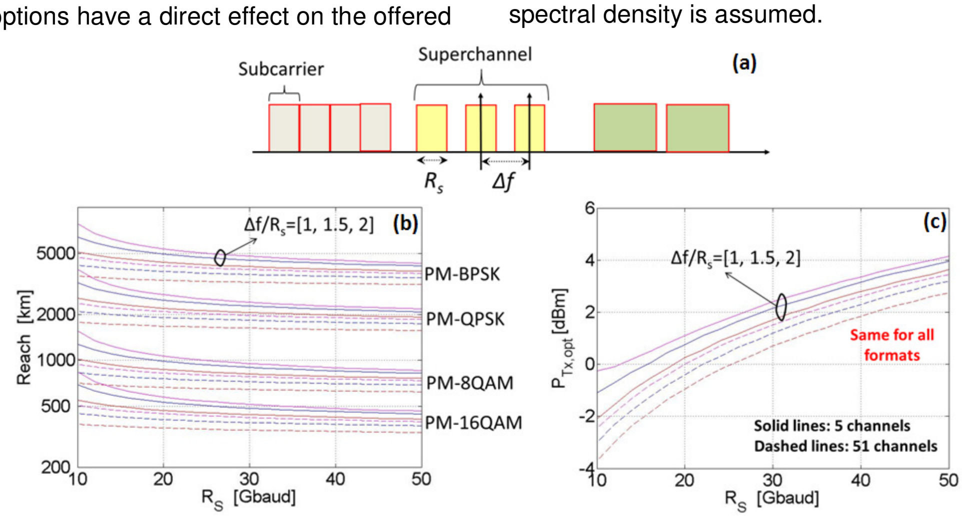

Fig. 1: (a) Superchannels consisting of multiple optical carriers, (b) The maximum reach as a function of the symbol-rate for the optimum launch power per subcarrier, (c) The optimum launch power per subcarrier as a function of the symbol-rate.

Physical Layer Design Parameters

Superchannels consisting of multiple optical subcarriers are depicted in Fig. 1(a). Each superchannel is characterized by the symbol rate (R_s) and the modulation format of its subcarriers, as well as the spacing between the optical subcarriers (Δf). In order to determine the maximum transparent reach that a superchannel can achieve, various parameters need to be examined. This problem becomes more complicated when considering the presence of other superchannels.

In the following we describe the assumptions of our analysis. Each span is composed of 80 km of SSMF fiber, with a total span loss of 25 dB, followed by an EDFA with noise figure of 6 dB. The reference BER is set to $2.4 \cdot 10^{-3}$ (Q=9 dB). The symbol rate is varied between 10 Gbaud and 50 Gbaud. Different cases are examined for the spacing between the optical carriers (corresponding to $\Delta f/R_s$=[1,1.25,1.5,1.75,2]). The considered modulation formats include: PM-BPSK, PM-QPSK, PM-8QAM, and PM-16QAM.

The maximum reach for the optimum launch power per subcarrier, obtained using the theory presented in [2], is depicted in Fig.1 (b). The effect of the modulation format, the symbol rate, the subcarrier spacing, and the total number of subcarriers is presented. While multiple different options seem to be available in Fig. 1(a) for a network planning algorithm to select from, this is not exactly the case. In fact, these options are available only assuming to operate at the optimum launch power P_{opt} for each case. However, P_{opt} varies a lot with the symbol-rate, as it is shown in Fig. 1(c). As a result, by setting a constant launch power for all cases, “penalties” would be introduced in terms of the maximum transparent reach. On the other hand, by setting the optimum launch power for each case, the system design becomes impractical due to limitations at the amplification stages.

We propose a solution to this problem based on the interesting finding is that the power spectral density (defined as the ratio between the launch power per subcarrier and the subcarrier spacing) varies to a significantly smaller degree than P_{opt}. This means that the optimum launch power condition for all symbol-rates and all modulation formats corresponds to an almost constant power spectral density. Thus the possibility is offered to deploy transponders operating at different symbol-rates and modulation formats within the same network.

Network Planning Case Studies

In the following we proceed to quantify the impact of physical layer design parameters via conducting case studies on the network scale. An extended version of the simulated-annealing based heuristic RMLSA algorithm[3] is applied. In the extended version two different optimization objectives are defined: (i) spectrum minimization and (ii) transponder minimization. One is selected as the primary objective, while the other serves as the secondary objective. If multiple solutions satisfy the primary objective, then the solution performing better in terms of the secondary objective is selected.

The Deutsche Telekom reference core network[3] (consisting of 14 nodes and 23 bidirectional links) is selected and the traffic matrix for 2010 is scaled in order to obtain different average internode traffic demands. The considered modulation formats include: PM-BPSK, PM-QPSK, PM-8QAM, and PM-16QAM. Symbol rates are considered within the range of (10-50) Gbaud with steps of 8 Gbaud. In the presented case studies, a spectrum slot size of 1 GHz is selected. The inter-carrier spacing is set to the symbol rate. Additionally, the maximum number of subcarriers that can be generated by one transponder is set to 8. Finally, an overhead of 11% (FEC and protocol overhead) is assumed in terms of capacity.

Two basic options are identified depending on whether the symbol rate is fixed or variable. In the case where the symbol rate is fixed, optimum launch power conditions are assumed. In the case where the symbol rate is varied, different levels of constant power spectral

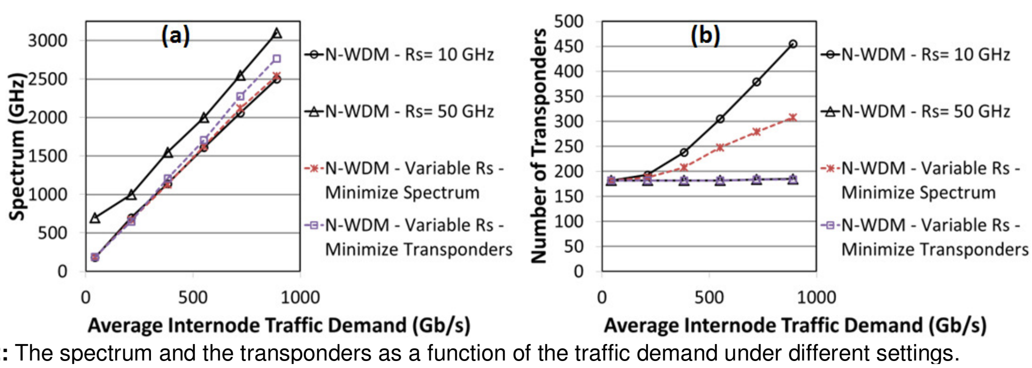

Fig. 2: The spectrum and the transponders as a function of the traffic demand under different settings.

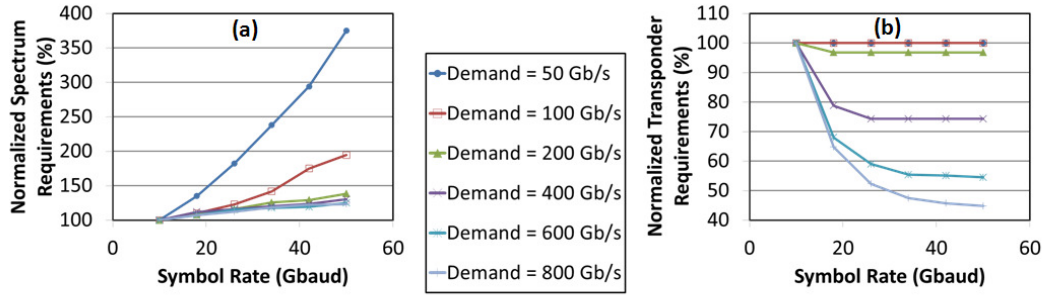

Fig. 3: The normalized spectrum and transponder requirements for the fixed symbol-rate option under different values of average inter-node traffic demand. Normalization is conducted with respect to the 10 GHz case.

density are examined. It is found that setting the power spectral density at 25 μW/GHz leads to reach values having a penalty less than 0.5% compared the reach obtained for the optimum launch power.

First, we examine the case in which the symbol rate is fixed and proceed to tackle question (1). In Fig. 2(a) and 2(b) the utilized spectrum and the required transponders are respectively presented as a function of the traffic demand under different settings. It is observed that increasing the symbol rate from 10 GHz to 50 GHz, leads to up to 275% higher requirements on spectrum. This is caused by the fact that higher symbol rates imply coarser granularity of the offered bit-rates. Hence, for higher symbol rates the optical carriers cannot be as effectively filled. This effect is less pronounced as the traffic demand increases. On the other hand, higher symbol rates lead up to 55% reduced requirements on transponders - as the maximum offered capacity of each transponder increases with the symbol rate.

In order to quantify the occurring tradeoff, we present the normalized spectrum and transponder requirements as a function of the symbol rate for different traffic demand values in Fig. 3(a) and 3(b). For each traffic demand the spectrum (/transponder) requirements are normalized to the spectrum (/transponders) corresponding to the 10 GHz case. Assuming for example an average traffic demand of 800 Gb/s, it can be observed that selecting a symbol rate of 50 GHz leads to 55% savings in terms of the number of transponders compared to the 10 GHz case. These savings come at the expense of a 23% penalty in terms of utilized spectrum. However, for average traffic demands less than 100 Gb/s, there is no incentive in terms of transponder savings to move to higher symbol-rates. It is noted that modifying the primary optimization objective from spectrum minimization to transponder minimization has only a minor impact for the fixed symbol rate case. Thus, only the results for the spectrum minimization are presented for these cases.

We, now, proceed to tackle question (2) and examine the cases in which the symbol rate is allowed to vary. In Fig. 2(a) and 2(b) the results are presented for two different primary optimization objectives: (i) spectrum minimization and (ii) transponder minimization. When objective (i) is selected, the minimum utilized spectrum is achieved (as in the fixed 10 GHz case). However, the number of required transponders is up to 48% less than the required transponders for the fixed 10 GHz case. In case objective (ii) is selected, the minimum required transponders are achieved (as in the fixed 50 GHz case). However, the utilized spectrum savings compared to the fixed 50 GHz case range between 11% and 73% (depending on the traffic demand). Hence, we have shown that allowing the symbol rate to vary leads to savings both in terms of spectrum and transponders.

Conclusions

We focus on the promising N-WDM concept and proceed to quantify the effect of physical layer design parameters on the network level. Case study results from a realistic reference core network are presented. Significant transponder and spectrum savings can be achieved by allowing the symbol rate to be dynamically tuned. This is possible when a fixed power spectral density is assumed - with only minor penalties in terms of transparent reach. Additionally, under different settings the occurring trade-offs between the utilized spectrum and the transponders are identified.

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